

# Budgeting Postglacial Sedimentation History on the Santa Cruz, California mid-Continental Shelf

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**Abstract-** High-resolution seismic reflection profiling and surface texture mapping of the central California continental shelf, reveal a prominent subsurface reflector interpreted as a low stand erosion surface and an overlying mudbelt that covers 421 km<sup>2</sup> of the mid-shelf in depths of 40-90 m. Radiometric and sedimentologic analyses of samples from vibracores taken along the seaward edge of the mudbelt show that initial deposition above the pre-Holocene erosion surface began ca. 14.5 ka. These data and model results of sea-level history, tectonics, and the Monterey Bay littoral sediment budget support the notion that the entire midshelf deposit was formed during the postglacial transgression. An alternative explanation, that <30% of the deposit is Holocene, requires that (1) sediment input is overestimated and/or loss is greatly underestimated, and (2) preservation on the shelf was significant despite deep and active wave scour observed in the form of rapid cliff and bedrock cutting early and late in the transgression. The difference between a basal age of ~14.5 ka and residence time of midshelf sediment (3,273 years), derived from dividing mudbelt volume by modern accumulation rate, implies: (1) significant sediment loss occurred since the mudbelt formed and/or (2) sediment accumulation has varied greatly over time. Although modern sediment budgets are relatively well constrained, it remains uncertain how well we can apply them to the past. An evolving model of sedimentation history explores the likelihood of changes in sediment supply, accumulation patterns, and depositional patterns owing to postglacial sea-level history and human land-use activities while providing important boundary conditions for modeling shoreface evolution.

## I. INTRODUCTION

Improving our understanding of the natural variability and processes of shoreface evolution is essential to better predict coastal change, manage coastal resources, and assess the impact of both natural processes and human activities on coastal ecosystems. In addition to primary forcing by sea level, tectonics, and sediment supply, abiotic and biotic factors including antecedent morphology and geology, wave climate and circulation, and benthic biologic agents control shoreface change and sediment accumulation. In active margin settings with high sediment input and wave exposure, a significant portion of the coastal sediment budget may be transported offshore onto the shelf and slope [1, 2], providing archives of coastal and shelf sedimentation owing to ~120 m of postglacial sea-level transgression during the last 21 ka [3]. In an attempt to identify the controls on and quantify the rates of shoreface adjustment and sediment redistribution along the

central California coast, we are developing a model of postglacial sedimentation history on the continental shelf of Monterey Bay. This site was chosen because it is an active-margin setting characterized by moderate sediment input and wave exposure, and because extensive mapping and sediment sampling in the Monterey Bay National Marine Sanctuary provides important data for reconstructing change to the coast and continental shelf (see [4, 5] for detailed review of the study and data collected). This system is characterized by an extensive mid-shelf sedimentary deposit in depths of 40-90 m that reaches up to 35 m thick. It provides an archive of (1) depositional processes associated with postglacial sea-level transgression, and (2) changes to substrate types that serve as important habitat for commercially-important, long-lived rockfish which are currently threatened by over-fishing and habitat degradation.

## II. SETTING

Crescent-shaped Monterey Bay is bounded by the mudstone and sandstone cliffs of Santa Cruz in the north and the granitic headland of Monterey Peninsula to the south [6]. Seismic reflection profiling and mapping show that basement structures composing the Monterey shelf and lower coastal Santa Cruz Mountains are sequences of Miocene to Pleistocene sedimentary rocks displaying steep, seaward-dipping strata and are cut by northwest-southeast en echelon folds and faults [7, 8]. These structures and the stair-stepping succession of uplifted marine terraces northwest of Santa Cruz are consistent with right-lateral wrench faulting that characterizes the strike-slip movement at the Loma Prieta Peak-restraining bend of the San Andreas Fault [9]. Radionuclide analyses show that the marine terraces have uplifted at an average rate of 1.1 mm/yr over the late Quaternary [10]. Several sources of sediment to the littoral zone have been identified [11-15] and a preliminary sediment budget has been proposed [16]. The transport pathways and fate of sediment depends upon sediment type. Fine sand and silt are advected seaward to the mid-shelf mudbelt (Fig. 1), while coarser sediments are transported south and ultimately down the Monterey Canyon [17]. Sediment bypassing across-shelf may occur, particularly during strong winter re-suspension events, but the magnitude of this process and sediment loss to Soquel Canyon remains uncertain [18].

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### III. RESULTS

#### A. Shelf morphology and mudbelt stratigraphy

The central California continental shelf is characterized by a prominent subsurface acoustic reflector, which truncates the steeply dipping strata comprising the bedrock of the outer shelf and coastline and is interpreted as the pre-Holocene erosion surface [4, 7, 19-21]. Fig. 2 shows a representative cross-shore profile of the Santa Cruz shelf (A-A' in Fig. 1) interpreted from seismic reflection profiling, multibeam mapping, and analyses of vibracore samples. The morphology of this erosion surface (dashed line) is highly irregular and complex along- and across-shelf, and exerts an important control on sediment accumulation. It slopes gently in the nearshore and outer shelf but displays a prominent, high relief (~25 m) wall 6 km seaward of the modern shoreline. The modern seafloor (solid line) is smooth and gently sloping and in places a subtle acoustic reflector can be seen parallel to it 3-10 m below the surface. The midshelf deposit varies from <5 m to >35 m thick along and across the shelf and fine sand on the surface grades to silt at about 50 m depth. The postglacial eustatic sea-level curve (dotted line) and Meltwater Pulses (MWP) 1A and 1B (hatched bands) that delineate rapid sea-level rise events (30 - 45 mm/yr, [3]),

are fixed to the seismic profile at the (1) glacial low stand (-120 m depth, 21 ka) and (2) modern sea-level position obtained at ~5 ka (note the age scale of sea-level history along the top x-axis). Also shown are the paleo-positions (corrected for regional uplift) of the pre-Holocene erosion surface at 11.9 ka (onset of MWP-1B) and 14.7 ka (onset of MWP-1A). Four unique depositional units are identified within the mudbelt based on their acoustic signature, sedimentology, composition, and age.

#### B. Shelf evolution and mudbelt deposition history

A distinct feature of the pre-Holocene erosion surface is a steep wall found between ~40 and 65 m below modern sea level (Fig. 2). This is interpreted to be a paleo-seacliff drowned during MWP-1B ca. 11.5 ka when rapid rates of sea-level rise would have helped to preserve a cliff morphology, in contrast to the low rates of rise that typify the early and late stages of transgression, which resulted in the uniformly low-sloping outer and inner shelves [20]. Initial formation of the midshelf deposit began after ~15 ka with the deposition of a shallow-marine facies along the outer mudbelt margin [22]. Along 15 km of the seaward margin, vibracore samples show a sharp lithologic unconformity between the basal shallow-marine facies and an overlying highstand massive silt apron.

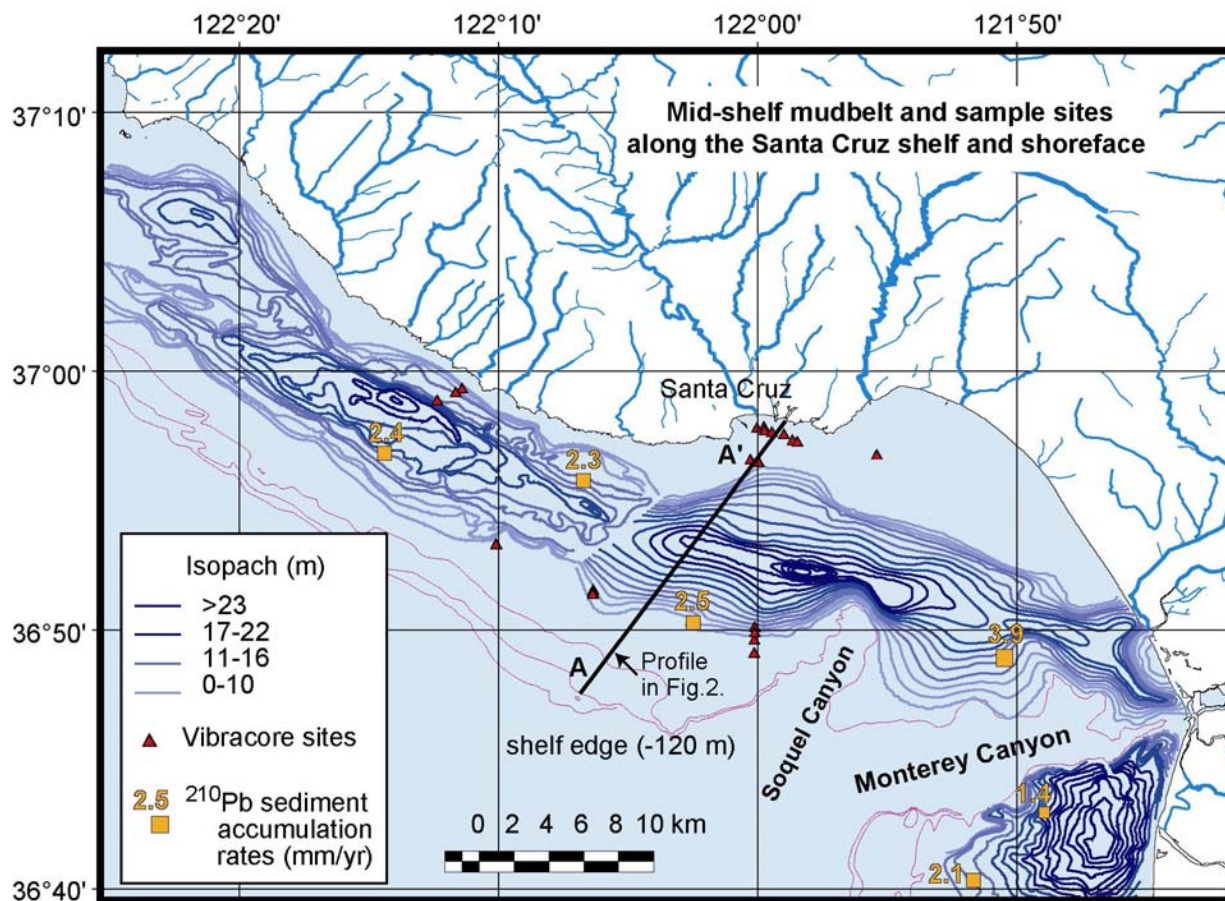


Fig. 1. Map showing mid-shelf mudbelt thickness, shelf morphology, and sample sites including vibracores used for  $^{14}\text{C}$  dating (triangles) and box cores for  $^{210}\text{Pb}$  analyses (squares).

The unconformity is dated at ~11.5 ka by extrapolating sediment accumulation rates derived from  $^{14}\text{C}$ -dated samples of the basal facies upcore [22]. This is consistent with abrupt drowning of the outer shelf during MWP-1B and rapid transgression (relocation) of the shoreline >3 km landward as sea level overtopped the paleo-seacliff. The stratigraphic relation of these facies within the central portion of the shelf and sediment deposit remains unclear.

If the midshelf deposit is entirely of postglacial age, then the dominant period of accumulation likely occurred during or soon after the Younger Dryas (~12 ka) with fluvial and deltaic contributions from streams discharged at or near the top of the paleo-seacliff. Extensive progradation observed in seismic facies and constrained by basal  $^{14}\text{C}$  ages would be consistent with high sediment input shed from the shallower, inner shelf and significant preservation potential afforded by new accommodation space at the base of the drowned paleo-seacliff following MWP-1B. High sediment discharge in the early and middle transgression is supported by paleoclimate studies that indicate significantly wetter climate in California at that time [23-25].

Average sediment accumulation rates (calculated by dividing mudbelt thickness by time since postglacial sea level first flooded the shelf) range 0.1 to 2.5 mm/yr. These are minimum rates because initial deposition lagged ~1 to

1.5 ka behind and 8-15 m below sea level as indicated by  $^{14}\text{C}$  ages of basal mudbelt sediments. Sediment accumulation rates derived from  $^{14}\text{C}$  dates of calcareous sediments in cores range 0.1 to 2.0 mm/yr, and in some cases represent minimum rates where dated samples were in transport prior to deposition. Importantly, these long-term average accumulation rates that range >1 order of magnitude vary significantly across and along the Monterey shelf, in contrast to modern  $^{210}\text{Pb}$ -derived sediment accumulation rates that are uniformly high (2.3-3.9 mm/yr) across the mudbelt [26]. The discrepancy between uniform accumulation today and highly variable accumulation over the Holocene, however, suggests (1) important processes operating across- and along-shelf partition sediment within mudbelt depths and (2) variability in long-term sedimentation is not captured by modern sediment tracers and sedimentation proxies.

### C. Paleo-sediment budgets and model development

We are developing a 3-dimensional large-scale geometric-process model to examine sediment budgets and transport over annual to millennial time scales by incorporating (1) quantitative measurements of modern sediment sources, fluxes, and shoreface processes; and (2) paleo-environmental reconstructions based on geophysical mapping, sedimentologic analyses, radiometric dating, and

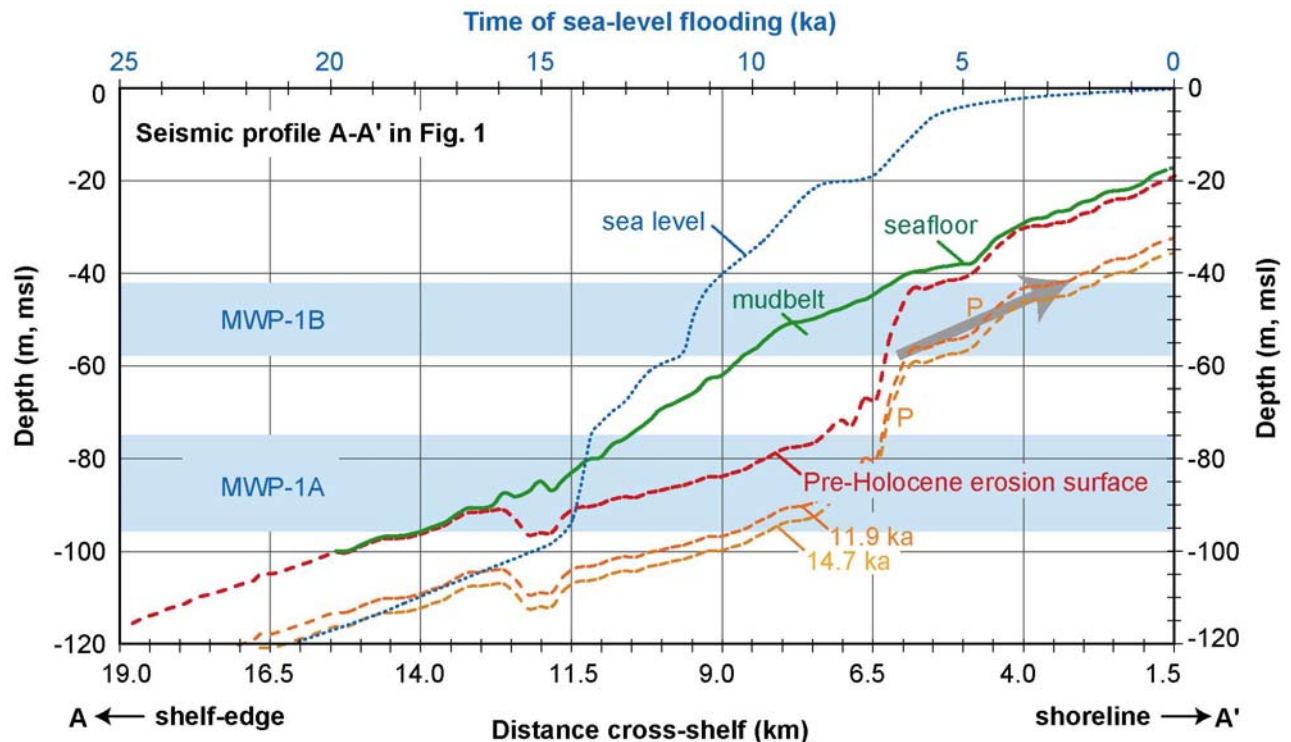


Fig. 2. Postglacial sea-level history and shelf morphology offshore of Santa Cruz Point, California (profile A-A', Fig. 1). Present seafloor topography and mudbelt surface (solid line), eustatic sea-level (dotted line) and Meltwater Pulses 1A and 1B (hatching) from Bard et al. (1990), and present depth and uplift-corrected paleo-positions of pre-Holocene erosion surface at 11.9 and 14.7 ka, respectively (dashed lines). Overtopping of the paleo-seacliffs (P) at 11.5 ka led to rapid relocation of the shoreline more than 3 km landward (arrow), and is consistent with abrupt lithologic transition in cores of outer mudbelt (see text).

geophysical modeling. We constrain boundary conditions in the past based on modern shelf characteristics (e.g. the relationship between sediment grain size distribution and accommodation space on the shelf today [22]), and compare rates and magnitudes of past coastal change with modern observations to assess variability in sediment budgets and shoreface processes. For example, we can test whether the volume of sediment required for the formation of an extensive progradational wedge within the midshelf deposit between 12 and 6 ka is consistent with modern rates of input. Extrapolating over the length, and average thickness and width of the mudbelt,  $0.5$  to  $1.5 \times 10^6 \text{ m}^3$  of sediment would have been added to the mudbelt each year, well within modern rates of accumulation; in fact, the higher rate more effectively balances the calculated modern littoral sediment budget, suggesting that (1) less accommodation space exists today on average across the shelf, (2) greater accumulation occurs in localized settings of the mudbelt, and/or (3) greater loss occurs today than in the past. These results provide the following hypotheses to test: (1) sediment accumulation is greater today along the seaward mudbelt margin than elsewhere, and (2) Sequoia Canyon is a net sink capturing sediment at half the rate of Monterey Canyon ( $0.5 \times 10^6 \text{ m}^3/\text{yr}$ ). Sensitivity tests that explore the variability in climate and sea-level changes during deglaciation, their influence on depositional patterns, littoral and shelf circulation, sediment supply from rivers, and wave climate may identify the model parameters of greatest uncertainty in need of refinement. The results of this modeling effort will also help guide process-oriented morphodynamic modeling.

#### IV. CONCLUSIONS

Seismic reflection profiling and analyses of composition, texture, and age of shelf sediments reveals that a highly complex shelf morphology along the central California shelf formed since the last glacial maximum 21 ka. Gradual rates of sea-level rise early and late in the transgression cut wide shelf platforms while abrupt MWP 1A and 1B led to the drowning of a steep paleo-seacliff that was retreating at the shoreline ca.  $\sim 14.7$  ka. Subsequent sediment accumulation on this erosional surface began sometime after  $\sim 15$  ka and was characterized by early deposition of coarse, shallow-marine, shell-rich facies. It currently remains uncertain, whether the bulk of the midshelf deposit was formed by rapid progradation of deltaic and/or fluvial sediments once sea level overtopped the drowned paleo-seacliff (11-6 ka) or if a large component of the deposit predates the transgression. We hope to test this by examining facies relationships and ages in core samples to be obtained from the central midshelf. These results will shed light on the complex sedimentation dynamics on the shelf as well as preservation potential during sea-level movements.

Long-term average sediment accumulation rates vary significantly across and along shelf, in contrast to modern  $^{210}\text{Pb}$  rates that are uniformly high across the entire

mudbelt. This suggests that modern sediment tracers and sedimentation proxies provide insight on sediment input, but are not necessarily representative of long-term sediment accumulation patterns. Reconstructions of depositional history based on geophysical and sedimentologic data illustrate that past rates of shoreface adjustment and sediment accumulation have significantly exceeded modern rates and suggest that the resulting deposition was complex both across and along shore. As a result, there is a great need to understand natural variability in sediment accumulation histories by examining geologic archives of sedimentation.

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